TUNABLE SUBWAVELENGTH RESONANT GRATING FILTER

Government Interest

Cross Reference to Related Applications

This application claims the benefit of United States Provisional Patent Application Serial No. 60/415,048 filed by Stephen Y. Chou *et al.* on September 30, 2002 and entitled "Optical Filters With Fixed and Tunable Frequency," which is incorporated herein by reference.

Field of the Invention

This invention relates to optical filters known as subwavelength resonant grating filters (SRGFs) and, in particular, to tunable SRGFs.

Background of the Invention

Optical filters are key components in a wide variety of optical systems including optical telecommunications, optical displays and optical data storage. An optical filter is used to selectively reflect or transmit light of a predetermined wavelength. Typical uses include channel selection in wavelength division multiplexed (WDM) systems, multiplexers, demultiplexers, switches and wavelength selective laser cavity reflectors.

Subwavelength resonant grating filters (SRGFs) are highly promising for many optical filter applications. SRGFs typically comprise a linear array of grating lines overlying an optical waveguide. The spacing between successive grating lines is smaller than the wavelength of the light they process, hence they are called subwavelength gratings. They are highly reflective for light of a specific wavelength that resonates with the spaced grating lines. Further details concerning such filters can be found, for example, in United States Patent No. 5,216,680 issued to Magnusson *et al.* on January 1, 1993 and United States Patent No. 5,598,300 issued to Magnusson *et al.* on January 28, 1997, which are incorporated herein by reference.

While SRGF's are compact and highly reflective, they are typically fixed in resonant wavelength at their fabrication. Efforts have been made provide a tunable SRGF by disposing an electro-optic medium adjacent the grating. See United States Patent No. 6,215,928 issued to A. Friesem et al. on April 10, 2001. Unfortunately the Friessem et al structures do not perform sufficiently well for practical application. Accordingly, there is a need for an improved tunable subwavelength resonant grating filter.

Summary of the Invention

In accordance with the invention, a tunable subwavelength resonant grating filter comprises a liquid crystal cell having a pair of major surface walls. One wall of the cell is a coated subwavelength grating of the filter. The coating fills the grating trenches to facilitate uniform alignment of the liquid crystal material. The refractive index of the

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LCD material in the cell can then be electrically or thermally adjusted to tune the resonant wavelength.

Brief Description of the Drawings

The nature, advantages and various additional features of the invention will appear more fully upon consideration of the illustrative embodiments not to be described in connection with the accompanying drawings. In the drawings:

Fig. 1 is a schematic cross section of a tunable LCD SRGF in the field-off condition;

Fig. 2 shows the device of Fig. 1 in the large field condition; and

Fig. 3 is a schematic illustration of an advantageous SRGF for use in the tunable grating of Fig. 1.

It is to be understood that these drawings are for purposes of illustrating the concepts of the invention and are not to scale.

Detailed Description

Applicants have discovered that the grating structure in an LCD cell can prevent proper alignment of the liquid crystal material, interfering with proper functioning of an LCD tunable SRGF. This interference can be substantially eliminated by planarizing the grating, as by coating it with a polymer to fill the grating trenches.

Referring to the drawings, Fig. 1 is a schematic cross section of a tunable subwavelength resonant grating filter 100 comprising, in essence, an LCD cell 101 having as one major surface wall a coated subwavelength grating 102 of a SRGF 103.

The cell 101 comprises a second major surface wall 104 and is filled with LCD material 105. The SRGF comprises, in addition to the grating layer 102, a planar waveguide 106 parallel to the grating plane. In this embodiment, transparent electrodes 107 and 108 are disposed on opposite sides of the LCD material to permit voltage control of the LCD index of refraction. A polymer coating layer 109 fills the trenches in grating 102, and surfactant coatings 110 on the major cell wall surfaces are provided to permit alignment of the liquid crystal material (homeotropic alignment). A voltage source 111 between electrodes 107, 108 can control the index of the LCD material 105 and thus tune the resonant wavelength of the filter 100. Advantageously a cladding layer 112 separates the electrode 108 from the waveguide layer 106. The SRGF may conveniently be disposed on a transparent substrate 113.

The major surface walls 103, 104 comprise transparent dielectric materials such as glass. The grating layer 102 and the planar waveguide 106 are also transparent dielectric materials with the waveguide material having a higher index of refraction than the grating material. The grating itself can be patterned as a conventional linear array of parallel grating lines or as a two dimensional array of nanoscale diffraction elements with subwavelength spacing. The advantage of the two dimensional array grating is substantial polarization independence.

In a preferred embodiment, the cell wall 104 and the substrate 112 are comprised of glass, and the electrodes 107, 108 are advantageously deposited coatings of transparent conductor such as indium tin oxide (ITO). The SRGF preferably comprises a patterned silicon nitride (SiN_x) grating layer 102 deposited and patterned to work as a resonant filter on an SiO_2 waveguide layer 106. An appropriate polymer to fill the trenches is a

polystyrene based resist (NP 60) and a compatibe surfactant is a silicone surfactant alignment agent such as ZLI 3334.

The operation of the tunable SRGF can be understood by consideration of Figs. 1 and 2 showing the device with different levels of electrical field strength between the electrodes 107,108. In Fig. 1, where no electrical field is applied, the liquid crystal molecules are aligned primarily by the effect of surfactant coatings 110. The LC material aligns parallel to the normal direction between the coatings 110. In this state, light entering the cell through either transparent cell wall experiences the minimum refractive index of the variable index LCD material.

Fig. 2 shows the cell in a field where the voltage is large. Here most of the liquid crystal molecules will rotate to a direction where the direction is perpendicular to the electric field. Only on the surface there is a thin layer of liquid crystal molecules with their directors parallel to the cell normal. In this condition light incident normal to the cell will experience the maximum refractive index of the LCD material during much of its passage through the cell. For field strengths intermediate zero and large, the light will experience intermediate indices. Since the working wavelength of the resonant grating depends on the refractive index of the LCD cell, the working wavelength of the filter can be tuned by the applied electrical field. Alternatively, the LCD index can be controlled thermally by an electrically powered heat source or magnetically by an electromagnet.

Fig. 3 illustrates in greater detail the features of an advantageous SRGF for use in the tunable filter of Figs. 1 and 2. The primary advantage of using the Fig. 3 SRGF is that the resulting tunable filter can be made polarization independent.

Referring to Fig. 3 the filter 30 comprises a waveguide layer 31 and a grating layer 32 adjacent the waveguide layer. The grating layer is patterned into a two-dimensional array of nanoscale diffraction elements 33. The array of elements 33 forms a two-dimensional grating structure that is periodic in two orthogonal directions (x,y). It has a period D_x in the x-direction less than a wavelength of the light to be processed and a period D_y in the y-direction less than a wavelength. The subwavelength periods D_x and D_y are preferably but not necessarily equal. The waveguide layer 31 can be conveniently formed overlying an optional substrate layer 34.

Each of the layers 31, 32, 34 advantageously comprises a transparent dielectric material. The waveguide layer index of refraction, n_2, should be greater than the grating layer effective index, n_{eff}, and greater than the substrate index, n_3.

The diffraction elements 33 (also referred to as grating elements) are advantageously circular pillars of nanoscale diameter, but could alternatively be nanoscale elements of other shape such as rectangular pillars, pyramids, cones or holes so long as the array exhibits subwavelength periodicity in two orthogonal directions. The diffraction elements are coated with a planarizing layer 35, such as a polymer, and the planarized surface is coated with a layer of surfactant (not shown).

In an exemplary device for light of 1.55 micrometer wavelength, the substrate can be glass, the waveguide layer SiO_2 and the grating layer composed of nanoscale diameter pillars of silicon nitride. Typical dimensions are: pillar diameter - 100 to 600 nanometers; pillar height - 20 - 200 nanometers; pillar spacing 200 nanometers to 1.2 micrometers. Alternatively, the device can be implemented in semiconductor materials

such as InGaAsP/InP. Such devices can be readily fabricated using the nanoimprint lithographic techniques described in United States Patent No. 6,482,742 (Nov. 19, 2002) and United States Patent No. 5,772,905 (June 30, 1998) which are incorporated herein by reference. The fabrication of such filters using nanoimprint techniques is described in applicants' United States Patent Application Serial No. _____ filed contemporaneously herewith and entitled "Method of Making Subwavelength Resonant Grating Filter", which is incorporated herein by reference.

In operation, light is shone onto the filter 30, typically at normal incidence to the plane of the grating layer. Since the grating elements are arrayed with subwavelength spacing, the light will experience the grating layer as an effectively homogenous layer with an effective index n_{eff}, and, except for light at a certain resonant wavelength λ_o, the light will transmit through the device as if it were a thin-film structure.

For light at the resonant wavelength λ_o, the diffraction from the grating elements produces an evanescent wave along the x-y plane. The evanescent wave couples with a waveguide mode supported by the waveguide layer, propagating a waveguide mode within the waveguide layer. Due to the phase matching of the grating elements, the waveguide mode radiates energy transverse to the waveguide layer at a phase that interferes constructively with the reflection and destructively with the transmission. The result is that substantially all energy at λ_o is reflected and substantially no energy λ_o is transmitted.

An important advantage of this device is its polarization-independence. In conventional gratings with one-dimensional grating periodicity, only one polarization

component of the light can be coupled into the waveguide at a resonant wavelength λ_o. This is due to the difference between the TE and TM modes in the waveguide are different. Thus conventional filters are polarization dependent and transmit some of the light at λ_o.

With the two-dimensional grating filters described herein, both polarization components can be coupled into two orthogonal directions due to the symmetry of the grating. Therefore the filters are polarization independent and substantially all light at λ_o is reflected.

In designing such a filter for a particular application, the location of the resonant wavelength is determined primarily by the value of the grating period. In general,

$$\lambda_o = aD + b,$$

where λ_o is the resonant wavelength, D is the grating period and a, b are constants.

The bandwidth of the filter is determined primarily by the thickness h_1 (Fig. 1) of the grating layer. In general, the Full-Width-Half-Maximum (FWHM) of the filter follows a quadratic relationship of the grating thickness. It is thus possible to obtain a very narrowband filter by using a very thin grating layer. For example, a sub-nanometer FWHM can be obtained with grating thickness less than 60 nanometers.

For use with light incidence other than normal, polarization-independence is achieved by grating periods that are different in two orthogonal directions.

The advantages of this tunable filter are manyfold. It is easy to fabricate, potentially low in cost and provides good performance. The free spectral range can be large, making the device highly advantageous for DWDM systems. The large E-O efficiency of LC materials permits achievement of a relatively large tuning range with relatively low voltages, and with the use of the Fig. 3 SRGF, the tunable filter can be polarization independent.

It is understood that the above-described embodiments are illustrative of only a few of the many possible specific embodiments, which can represent applications of the invention. Numerous and varied other arrangements can be made by those skilled in the art without departing from the spirit and scope of the invention.